Appendix N.   Air Quality Background Information

AIR QUALITY BACKGROUND INFORMATION

Particle Size Terminology

Physical particle size is important to many industrial process operations. Pollution control and medical considerations, however, are more easily addressed by considering particle behavior rather than particle size. Two considerations of special importance to pollution control and medical evaluations are the rate at which particles settle in still air and the extent to which particles in a moving air stream will be removed by inertial impaction if the air stream follows a bent or curved path. Large, dense particles settle rapidly and are easily removed from an air stream by inertial impaction; small, low density particles settle very slowly and tend to follow a bent or curved air stream pathway.

Several particle diameter terms are used to describe particle size and aerodynamic behavior. Allen (1990) provides a partial list of 13 particle diameter definitions, only four of which reflect the actual physical dimensions of a particle. The other nine definitions refer to the diameters of circles or spheres with the same perimeter, surface area, volume, or surface-to-volume ratio as the actual particle or its image in a microscope. Unfortunately, most air pollution discussions refer only to particle size ranges without clarifying which technical definition has been used.

The definitions used or implied most frequently in ambient air quality discussions are presented below. A sieve diameter is usually implied when large particles have been mechanically sorted into size categories. Particle size determinations based on microscopic examination may reflect any of several definitions, with the projected area diameter being a common definition. Particle size information provided by ambient air quality sampling instruments usually refers to the aerodynamic equivalent diameter.

Sieve Diameter

The sieve diameter of a particle is the width of the minimum square aperture through which the particle will pass. Because many particles have complex physical shapes, the sieve diameter will often be larger than the minimum physical dimension and smaller than the maximum physical dimension of the particle.

Projected Area Diameter

The projected area diameter of a particle is the diameter of a circle having the same enclosed area as the outline of the particle (generally viewed or photographed through a microscope). Two different projected area diameter definitions are widely used. One definition is based on particles in a random orientation. The other is based on particles resting in a stable orientation.

Equivalent (Volume) Diameter

Because most suspended particulate matter has an irregular shape, the equivalent spherical diameter (generally referred to as the equivalent diameter) is used as a standardized description of physical particle size. The equivalent diameter is calculated by measuring the volume of a particle and computing the diameter of a sphere having the same volume. Some references use the term "volume diameter" instead of equivalent diameter.

Sedimentation (Stokes) Diameter

The sedimentation (or Stokes) diameter of a particle is based on the terminal settling velocity of a particle in still air. The sedimentation diameter is the diameter of a sphere having the same terminal settling velocity and density as the particle. Some references use the term "free-falling diameter" for evaluations based on the terminal settling velocity in fluids other than air.

Aerodynamic Equivalent Diameter

The aerodynamic equivalent diameter of a particle also is based on the terminal settling velocity of a particle in still air. The aerodynamic equivalent diameter is the diameter of a sphere with a density of 1 gram per cubic centimeter that has the same terminal settling velocity as the particle. Thus, the aerodynamic equivalent diameter differs from the sedimentation diameter of a particle whenever the real particle has a density other than 1 gram per cubic centimeter. For convenience, the term "aerodynamic equivalent diameter" is often shortened to aerodynamic diameter.

Quartz Grain Equivalent Diameter

Soil scientists occasionally use the term "equivalent diameter" when discussing particle sizes associated with wind erosion, but define the term differently than do atmospheric scientists. The term used by soil scientists is less ambiguous if phrased as "quartz grain equivalent diameter". Soil scientists calculate the quartz grain equivalent diameter by multiplying the sieve diameter of a particle by the density of the suspended particle or particle aggregate and dividing that product by the particle density of quartz (2.65

grams per cubic centimeter). If particle aggregates are being considered, the density of the aggregate is treated as a bulk density (including pore spaces within the particle aggregate).

Particle Size Ranges for TSP and PM$_{10}$

Until the mid-1980s, federal and state particulate matter standards applied to a broad range of particle sizes and were referred to as total suspended particulate matter (TSP) standards. The high-volume samplers used at TSP monitoring stations are most effective in collecting particles with aerodynamic diameters smaller than 30-50 microns, although larger particles also are collected (U.S. Environmental Protection Agency 1982, Lodge 1989).

Health concerns associated with suspended particles focus on those particles small enough to reach the lower respiratory tract (tracheobronchial passages and alveoli in the lungs) when inhaled. When breathing occurs through the nose, few particles with an aerodynamic diameter larger than 10 microns reach the lower respiratory tract. When breathing occurs through the mouth, particles with aerodynamic diameters as large as 20 microns may reach the lower respiratory tract (U.S. Environmental Protection Agency 1982). Not all particles with small aerodynamic diameters reach the lower respiratory tract; some are removed in the nasal passages, mouth, or upper throat regions.

Both the federal and state air quality standards for particulate matter have been revised to apply only to "inhalable" particles (generally designated PM$_{10}$) with a size distribution weighted toward particles having aerodynamic diameters of 10 microns or less. The particle size distribution implied by the PM$_{10}$ definition is intended to approximate the size distribution of particles that reach the lower respiratory tract. The State of California converted from a TSP standard to a PM$_{10}$ standard in 1983; the federal government converted from a TSP standard to a PM$_{10}$ standard in 1987.

It is difficult to relate the former TSP and current PM$_{10}$ standards to a precise range of physical particle sizes. Although the TSP designation does not have any obvious particle size connotations, the use of the word "total" in total suspended particulate matter implies 100% collection efficiency over a large range of particle sizes. As explained below, very few particle sizes are sampled with 100% efficiency by a TSP sampler.

The PM$_{10}$ designation seems to imply a rather precise size limit. The most widely quoted definition of PM$_{10}$ is "particulate matter smaller than 10 microns in (aerodynamic) diameter." Unfortunately, that simple definition is incorrect. The only absolute size limit that can be established for PM$_{10}$ is substantially larger than 10 microns.

The true definitions of TSP and PM$_{10}$ are derived by considering the equipment used to collect samples of suspended particulate matter.

Sampling Criteria for TSP and PM$_{10}$ Collectors

Both the former TSP standards and the current PM$_{10}$ standards have been defined primarily by the type of equipment used to collect suspended particulate matter samples. The sampling equipment incorporates inlet designs intended to exclude particles with large aerodynamic diameters. Because aerodynamic diameters are not an actual physical dimension, perfect screening of particle sizes is impossible. Some particles outside the target size range will be collected and some within the target size range will be excluded.

The performance of TSP and PM$_{10}$ sampling equipment is characterized by the "aerodynamic cutpoint diameter" of the collector inlet. The aerodynamic cutpoint diameter is the aerodynamic diameter at which the device excludes 50% of the mass of the corresponding ambient particles.

Design criteria for TSP samplers do not include tight tolerances on the size distribution of collected particles. Most TSP collectors have rectangular or square inlets with a peaked-roof precipitation shield. The design of standard TSP sampler inlets causes the cutpoint diameter of a TSP collector to vary with relative wind direction and wind speed.

No specific aerodynamic cutpoint diameter criteria were specified in the former federal TSP standards. Most references (e.g., U.S. Environmental Protection Agency 1982, Lodge 1989) indicate that TSP collectors have an aerodynamic cutpoint diameter of 30-50 microns under common wind speed conditions. The limited published literature on TSP collector sampling efficiency (Wedding et al. 1977, McFarland et al. 1979) implies a much broader range of aerodynamic cutpoint diameters (13-67 microns) depending on wind speed and relative wind direction. According to McFarland et al. (1979), the aerodynamic cutpoint diameter of TSP collectors decreases at high wind speeds and increases at low wind speeds.

The high-volume samplers used to monitor compliance with the current PM$_{10}$ standards have a narrow aerodynamic cutpoint diameter range of 9.5-10.5 microns. PM$_{10}$ samplers also incorporate round inlet designs that are not sensitive to relative wind direction. In addition, PM$_{10}$ samplers are much less sensitive to wind speed than are TSP samplers.

The 10-micron component of the PM$_{10}$ definition refers to a 50% collection efficiency measure, not an absolute size limit. When operated during wind speeds of 1-15 mph, an acceptable PM$_{10}$ sampler must collect 45-55% of the mass of particles with aerodynamic equivalent diameters of 9.5- 10.5 microns. In addition, the size-based collection efficiency curve derived for the sampler must pass a test for total particle mass collection. When the collection efficiency curve is applied to a standardized particle mass distribution, the calculated total mass of collected particles must be within 10% of the total mass calculated for the "ideal" PM$_{10}$ sampler collection efficiency curve. The standardized particle mass distribution used for the mass collection test includes particle sizes ranging from less than 1 micron to 45 microns in aerodynamic diameter.

Sampling Efficiency Curves for TSP and PM_{10} Collectors

Although the aerodynamic cutpoint diameter is useful as a single number for characterizing collector performance, proper understanding of the particle sizes collected by TSP and PM_{10} samplers requires a more complete description of collection efficiencies at various particle sizes.

Few studies have been performed to characterize the effectiveness of TSP samplers in collecting particles of various size ranges. Some of the studies that have been performed examined only a limited range of particle sizes. Figure N-1 illustrates the range of measured and extrapolated collection efficiencies for TSP samplers under variable wind speed and direction conditions.

The EPA definition of an ideal PM_{10} sampler is illustrated in Figure N-2. An ideal PM_{10} sampler would collect 50% of the particle mass present in the 10- to 10.5-micron aerodynamic diameter size range and would not collect any particles with aerodynamic diameters larger than 16 microns. In practice, most actual PM_{10} samplers will collect some particles with aerodynamic diameters of 25-30 microns (Purdue 1988, Lippmann 1989). The formal specifications for PM_{10} samplers imply an absolute aerodynamic diameter limit of 45-50 microns (40 CFR 53.43).

Figure N-2 includes representative upper and lower size distribution limits for PM_{10} sampler performance. Absolute upper and lower size distribution limits cannot be defined precisely because many different distribution curves can be drawn that meet both the cutpoint diameter and the 10% mass variation criteria. A sampler that collects 100% of all particles with aerodynamic diameters smaller than 10 microns and 0% of all particles with aerodynamic diameters larger than 10 microns would meet certification requirements but would not represent an ideal PM_{10} sampler.

Figure N-3 provides a comparison of collection efficiency curves for typical TSP and PM_{10} collectors. The collection efficiency curve for a typical TSP collector reflects varying wind directions and wind speeds predominantly in the 5-10 mph range.

HISTORICAL DESCRIPTIONS OF MONO BASIN CONDITIONS

I. C. Russell's Geological Study

Russell (1984) described the floor of the Mono Valley as a sloping plain with sage brush vegetation, scattered sand dunes, and a series of ancient beaches. Russell's reference to "dunes of drifting sand" implies that at least some of the sand dunes were not stabilized. The eastern shore of Mono Lake near Warm Springs was described as windrows of sand, gravel, and larval cases of the brine fly. The sand and gravel were characterized as volcanic in origin, with fragments of pumice.

Russell noted that on windy days Mono Lake was streaked with an alkaline froth. He described this froth as collecting on the leeward shore in a band "many rods wide and sometimes several feet thick" (a rod is 16.5 feet). He described "sheets of this tenacious froth" blowing inland through the desert shrubs "in fluffy masses that look like balls of cotton". When viewed from the surrounding mountains on a windy day, the fringe of white foam made the outline of the lake "unusually distinct".

Russell recognized tufa deposits as being a calcium carbonate precipitate formed under water. However, he failed to identify the factors that produced different physical forms of tufa deposits. He characterized tufa crags as being composed of three physical forms of tufa (lithoid tufa, thinolite crystals, and dendritic tufa), all of which are a calcium carbonate deposit. He noted that sands and pumice fragments along the lake shore were often cemented with an amorphous calcium carbonate deposit he called "stony" tufa. He also observed tufa-cemented sands and gravels in the terraces and beaches of former shorelines.

Russell mentions that efflorescent salts were found in two situations: in the exposed cavities of partially submerged tufa crags and in cave-like recesses in cliffs at water's edge, especially on Paoha Island. He characterized the efflorescent salts as being primarily sodium carbonate and sodium sulfate, in contrast to the calcium carbonate of tufa deposits. He also recognized that efflorescent salt deposits form only on porous substrates exposed to the air as capillary action draws salty water to the surface.

Other Written Accounts

Some other early accounts of Mono Lake make passing references to "alkali" deposits. A careful reading of these accounts reveals that the writers were usually describing tufa formations and amorphous tufa deposits, not alkaline salt deposits. Three examples of such accounts are presented below.

Browne (1961) described Mono Lake as it appeared in the mid-1860s, making several references to alkaline incrustations of calcareous deposits. Browne described former lakeshore strand lines as follows: "On the eastern shore low plains or alluvial bottoms, incrusted with alkali, show in distinct curvicular rims, composed of calcareous deposits, the gradual retrocession of the lake to its present level." (Browne 1961, page 49.)

Browne's drawings of the lake shore clearly show tufa towers. Browne described these lakeshore deposits as follows:

> The shores of Lake Mono, in the vicinity of the water, have a whitish color, arising from the prevalence of calcareous deposits [Browne 1961, page 48] . . . . The beach is strewn with beautiful specimens of boracic or alkaline incrustations. Weeds, twigs, stones, and even dead birds and animals, are covered by this peculiar coating, and present the appearance of coral formations. Some specimens that I picked up are photographic in the minuteness and delicacy of their details. . . . It is commonly supposed that these are

formations of white coral; but there is no doubt that they are produced by the chemical action of the water, which at frequent intervals is forced up through the fissures of the earth by subterranean heat. These springs are numerous, and probably form around them a base of calcareous matter, which by constant accretions rises above the surrounding level [Browne 1961, pages 49-51].

A brief but similar description of deposits on one of Mono Lake's islands (presumably Paoha Island) dates from 1865: "There are to be found, all over these islands, some of the most beautiful calcareous and alkaline incrustations, which form on the surface of everything that the water of either the lake or that emitted from the hot springs happens to come in contact with." (The Mining and Scientific Press, October 7, 1865, page 210.)

Chase (1911) provided a brief and rather cryptic description of the shore of Mono Lake: "The shores are whitened with alkaline incrustations, and the branches and twigs of dead trees that rise above the surface are petrified to the semblance of bone." (Chase 1911, pages 308-309.)

A map that accompanies Chase's book indicates that he reached the shore of Mono Lake by following a wagon road along Rush Creek. Thus, Chase's description is probably a reference to tufa deposits in the South Tufa or Lee Vining tufa areas.

While all the writers quoted above use the term alkali or alkaline, none of them make any specific mention of salts or salt deposits. The clear implication from these accounts is that many early observers used the term alkali as a synonym for any white mineral deposit.

SUPPLEMENTAL METEOROLOGICAL AND
AIR QUALITY DATA

Lee Vining and Simis Ranch Wind Patterns

Table N-1 summarizes seasonal and annual wind patterns for Lee Vining according to time of day. Table N-2 summarizes seasonal and annual wind patterns for Simis Ranch according to time of day.

Low Concentration PM$_{10}$ Events

Figure N-4 shows the monthly pattern of very low PM$_{10}$ measurements from the Simis Ranch monitoring station. Figure N-5 shows the monthly pattern of very low PM$_{10}$ concentrations from the Lee Vining monitoring station.

Observed Relationship between TSP and PM$_{10}$
Concentrations at Mono Lake

Table N-3 presents a detailed summary of the relationship between TSP and PM$_{10}$ concentrations at Simis Ranch. PM$_{10}$ concentrations have generally been 25%-75% of the concurrent TSP concentration. The average relationship between PM$_{10}$ and TSP concentrations does not vary significantly from low to high PM$_{10}$ concentrations. The range of PM$_{10}$-to-TSP ratios is greater at low PM$_{10}$ concentrations than at high PM$_{10}$ concentrations. There have been several instances when measured PM$_{10}$ concentrations exceeded measured TSP concentrations.

The wide range of PM$_{10}$-to-TSP ratios may result in part from artifacts of sample handling and analysis. The wide range of ratios may also reflect inherent differences in sampling effectiveness between PM$_{10}$ and TSP samplers. At very low particulate matter concentrations (especially those composed of small particle sizes), PM$_{10}$ samplers may be more efficient than TSP samplers; this would produce some PM$_{10}$ concentrations higher than the concurrent TSP concentrations.

Physical and Chemical Analyses of
Particulate Matter Samples

No comprehensive studies of the physical, chemical, or mineralogical characteristics of erodible substrates or suspended particulate matter in Mono Basin have been performed. Limited analyses have been performed on some particulate matter samples (Kusko et al. 1981, Kusko and Cahill 1984, NEA 1990) and a few soil samples (Kusko et al. 1981, Truesdail Laboratories 1981). A few soil samples have been analyzed for particle size distributions (Truesdail Laboratories 1981). One study of particle size distributions by the RJ Lee Group was available only as a summary document in court proceeding exhibits (Superior Court of the State of California for the County of El Dorado 1990). None of the chemical or particle size analyses have distinguished the mineralogical components of the material being evaluated.

None of the studies have analyzed particle densities (specific gravities) or have clearly described the procedures used to measure particle size; consequently, the available data are a mixture of sieve diameters, unexplained physical dimension measurements, and aerodynamic equivalent diameter.

Physical Characteristics

Truesdail Laboratories (1981) analyzed ten soil samples collected from various locations around Mono Lake. The general locations at which the samples were collected are indicated. No descriptions of the soil or sediment conditions at the sampling sites are included in the report. Table N-4 summarizes the particle size analysis results reported.

Actual suspended particulate matter samples collected by the GBUAPCD have been examined microscopically by the RJ Lee Group using manual and computer-controlled scanning electron microscope techniques. Most of the filter samples analyzed by the RJ Lee Group were PM_{10} samples; one filter sample from Simis Ranch and 11 filter samples from the Binderup site were TSP samples. The summary of the RJ Lee Group results does not describe the procedure used for measuring particle sizes, thus making the data difficult to interpret.

Chemical Composition

Several studies have included chemical analyses of soil samples or suspended particulate matter samples. All these chemical analyses, however, have been limited to elemental analyses and determinations of a few major ion groups (e.g., sulfates, nitrates, or chlorides). None of the studies have attempted to determine specific chemical compounds or mineralogical components.

Summary of Air Quality Monitoring Data Collected by the University of California, Davis

Data from air quality monitoring studies conducted in Mono County by researchers from the UC Davis are summarized in Table N-5. The sampling inlet for monitoring equipment used for this study had a nominal aerodynamic cutpoint diameter of 15 microns. Stacked filters were used to separate particles into two size categories. An upper filter allowed fine particles to pass through to a bottom filter. The upper filter provided an aerodynamic cutpoint diameter of 2.5 microns (Cahill et al. 1990). As discussed previously, aerodynamic diameters are not physical dimensions and aerodynamic cutpoint diameters represent a 50% collection efficiency, not an absolute size discrimination. For convenience, however, results from the two filters have been described as representing aerodynamic diameters smaller than 2.5 microns or between 2.5 and 15 microns. Combined results from the two filters provide a nominal PM_{15} measurement.

The nominal aerodynamic cutpoint diameter of the sampler inlet introduces a minor complication for comparing data to the current PM_{10} standards. The inlet for the stacked filter unit samplers used in the UC Davis studies have an aerodynamic cutpoint diameter of 15 microns in still air, decreasing to 11 microns at an ambient wind speed of 13.7 mph (Cahill et al. 1990). As a practical matter, the PM_{15} values reported by Kusko et al. (1981) are probably 25% higher than PM_{10} values. A more important complication affecting interpretation of the UC Davis data involves the duration of sampling.

As indicated in Table N-5, monitoring instruments operated continuously for 1-week periods during most of the study. PM_{15} data for multiday periods cannot be directly compared with the current 24-hour PM_{10} standards. Nevertheless, weekly average PM_{15} values above 40 Fg/m³ suggest the occurrence of at least one 24-hour episode of PM_{10} values above 50 Fg/m³. Multiday PM_{15} data for Lee Vining exceeded 40 Fg/m³ four times during the UC Davis study and were between 35 and 40 Fg/m³ two other times.

WIND EROSION PROCESSES

Dust Storms and Sand Storms

Meteorologists use the terms "dust storm" and "sand storm" to describe episodes of windblown particulate matter that significantly restrict visibility. Visibility limits of 0.5-7 miles are used by different agencies and authors in defining dust storm and sand storm events; a visibility limit of 1 kilometer (0.62 mile) is used more often than other visibility limits (Orgill and Sehmel 1976, Goudie 1978, World Meteorological Organization 1983). Dust storms and sand storms are generally differentiated by the size range of the suspended particles. Dust storms are dominated by particles with sieve diameters smaller than 100 microns; sand storms are dominated by particles with sieve diameters larger than 100 microns (World Meteorological Organization 1983).

Particulate matter concentrations associated with dust and sand storms vary substantially depending on proximity to the source area and the averaging time associated with the concentration measurement. Chepil and Woodruff (1957) report visibility estimates and measured dust concentrations for 24 dust storm events monitored in Kansas and Colorado during 1954 and 1955. The dust concentration measurements approximate a total suspended material estimate rather than a TSP or PM_{10} measurement. Dust storm events with visibilities of 1.3-4.8 miles had dust concentrations of 3,180-9,180 Fg/m³; events with visibilities of 0.5-1.25 miles had dust concentrations of 25,070-95,350 Fg/m³. Most dust storm events with visibilities of 0.25-0.5 mile had dust concentrations of 100,000-300,000 Fg/m³.

Chepil and Woodruff (1957) report particulate matter concentrations of 1,000,000 Fg/m³ and 1,327,000 Fg/m³ for the two largest dust storms monitored in Kansas during 1954; visibilities during these dust storms were 265-370 feet. Chepil and Woodruff (1957) also report particulate matter concentrations

of 353,000-583,000 Fg/m^3 for the three largest dust storms monitored in Colorado during 1955; visibilities during these dust storms were about 650-1,050 feet.

Chepil and Woodruff (1957) suggest that visibilities of about 1 kilometer are associated with dust concentrations of about 56,000 Fg/m^3. Orgill and Sehmel (1976) suggest that visibility reductions to about 7 miles are associated with dust concentrations of 3,000-5,000 Fg/m^3.

Meteorological conditions producing strong winds or significant vertical turbulence have the potential for producing dust storms of various sizes and durations. Weather conditions that typically have relatively short durations include various convective systems, such as squall lines and decaying thunderstorm cells. Windy conditions associated with the passage of warm and cold fronts have a somewhat variable duration. Strong mountain katabatic (downslope) wind conditions (e.g., Chinook and Santa Ana winds) also have somewhat variable durations. Windy conditions associated with strong regional pressure gradients sometimes persist for a few days.

General Mechanism of Wind Erosion

At a general level, wind erosion represents a transfer of energy from moving air to sediment and soil particles at the ground surface. At the scale of individual particles, wind erosion is the result of several interacting forces, some of which induce particle movement and others that resist particle movement. Lift, shear, and ballistic impact forces induce particle movement, and gravity, friction, and cohesion among particles resist movement. (The term "shear" as used in discussions of wind erosion processes is different from the term "wind shear" used to describe rapid changes in wind direction and velocity over short horizontal distances.)

Lift represents a difference in pressure between the top and bottom of a particle; shear represents a difference in pressure between the upwind and downwind sides of a particle. Lift represents forces producing vertical movement; shear represents forces producing horizontal movement. Together, lift and shear forces extract a particle from the ground surface and transport it downwind. Gravity and cohesion among particles resist lift forces while friction and cohesion among particles resist shear forces.

The pressure differences that generate lift forces are caused by vertical differences in wind velocity and by vertical turbulence in wind flow conditions. Friction at the ground surface causes wind speeds to be lower near the ground than at greater heights above the ground. The vertical changes in wind speed are associated with vertical changes in air pressure. Air moving at a higher velocity exerts a lower pressure than air moving at a low velocity. Small-scale vertical turbulence also produces temporary fluctuations in pressure that generate lift forces.

A very thin nonturbulent layer of air always exists immediately next to the ground surface. This layer, often called the laminar layer, is essentially a zone of calm air; its thickness depends on the roughness of the ground surface. Horizontal shear forces only affect objects that extend above or are lifted above this laminar layer. Rough surfaces and minor irregularities in smooth surfaces often result in some surface particles being perched partially or completely above the laminar layer. Sand-sized particles are often large enough to project into the turbulent wind flow zone above the laminar layer.

Three types of particle movement occur during wind erosion: surface creep, saltation, and suspension. Initial particle movement is generally by saltation. Saltation is a bouncing movement in which particles of moderate size are lofted slightly into the air and carried a short distance downwind before falling back to the ground. The impact of saltating particles helps initiate the saltation, surface creep (a rolling or sliding movement along the ground surface), or suspension movement of other particles. Surface creep and saltation are the dominant movement processes for large particles. Suspension is important for small particles. Wind erosion of most soils is dominated by saltation and surface creep.

Factors Affecting Erodibility of Sediments and Soils

Actual wind erosion rates are determined by a combination of wind conditions and the physical condition of the soil or sediment surface. The vertical profile of wind speeds and the extent of vertical turbulence are key wind components. The directional persistence of strong winds is also a factor, especially for surface creep and saltation processes. The most important aspects related to the soil or sediment surface include:

- # surface moisture conditions,
- # the extent of nonerodible surface material,
- # the extent of particle aggregation in the erodible material, and
- # the size of the exposed area.

Wet or frozen surfaces are essentially immune to wind erosion. Chepil and Woodruff (1963) determined that surface moisture levels above the permanent wilting point (15 atmospheres suction) effectively protect soil surfaces from wind erosion. Shikula (1981) examined the effect of atmospheric moisture levels on the threshold wind speed associated with dust storm events in Ukraine. Atmospheric moisture levels were characterized as a moisture deficit (the difference between actual water vapor pressure and the saturation vapor pressure level). A strong correlation was found between threshold wind speeds for initiating dust storms and moisture deficit levels. The threshold wind speed averaged 12.1 mph at a moisture deficit of 35 millibars, 19.9 mph at a moisture deficit of 25 millibars, 27.7 mph at a moisture deficit of 15 millibars, and 35.6 mph at a moisture deficit of 5 millibars.

The presence of nonerodible surface material (e.g., rocks, vegetation, or chemically cemented sediments) normally reduces the potential for wind erosion by reducing wind speeds near the ground and

blocking surface creep and saltation movements. However, very sparse coverage by nonerodible material may sometimes induce small-scale air turbulence that enhances the erosion of fine surface sediments by suspension.

Particle aggregation in erodible material can have complicated effects. The aggregates may result in surface characteristics that raise portions of the soil or sediment above the laminar layer. The size and density of the aggregates will also affect the minimum wind velocity necessary to initiate particle movement. Saltation, ballistic impact, and airborne collisions among aggregates often break the aggregates apart into particles small enough to be carried in suspension as opposed to saltation or surface creep.

The size and dimensions of areas susceptible to wind erosion also have some effect on wind erosion rates. These size factors are most important for surface creep and saltation processes and are less important for particle removal by suspension transport.

SALT DEPOSIT MINERALOGY

The mineralogy of salt deposit formations has been studied at several locations used for commercial extraction of various salts. Study results at one location can be extrapolated to other locations only if enough similarities exist among key salt chemistry factors. It is important to distinguish between salt deposits dominated by chlorides and those dominated by carbonates, bicarbonates, and sulfates. If chemical similarities are sufficient in this respect, more refined chemical similarities and differences must be considered. It is generally necessary to distinguish between calcium and sodium salts; differences in the relative amounts of potassium and lithium salts may also be important.

Differences between Owens Lake and Mono Lake Salt Deposits

Studies conducted at Owens Lake (Alderman 1985, Saint-Amand et al. 1986, Smith and Friedman 1986, Smith et al. 1987) have been especially useful in identifying processes that probably operate at Mono Lake. Mono Lake and Owens Lake are exposed to the same general climatic conditions, and both lakes were sodium-dominated with high carbonate and sulfate concentrations when salt deposits began to form. Evaluation of studies from Owens Lake, however, must recognize some important differences between these locations.

One difference is that the salt deposits at Owens Lake have been formed on a playa while those at Mono Lake have formed on sediments above a permanent lake. A playa is most accurately defined as the flat, generally dry, mostly barren, largely gravel-free floor of an interiorly drained topographic basin; portions of a playa may be subject to alternating periods of inundation and evaporative drying (Motts 1970, 1972; see also Academic Press Dictionary of Science and Technology 1992, Levin 1986, Bates and Jackson 1984). Surface substrates of playas are generally clays, silts, sands, or salt deposits.

The topographic distinction between a playa and a lakeshore helps explain an important difference between salt deposits at Owens Lake and those in Mono Basin. Salt deposits at these two locations formed in different hydrologic settings. The salt deposits at Owens Lake were formed primarily as underwater precipitates. The salt deposits at Mono Lake have formed as surface evaporative deposits in contact with air.

An underwater environment for salt formation will differ in several respects from a ground surface environment. Four considerations are especially relevant to comparisons between Owens Lake and Mono Basin:

the range of temperatures to which the deposited salt minerals are exposed and the rate at which the temperature changes after initial salt formation;

the amount of carbon dioxide available during and after initial salt formation;

the amount of water available for mineral transformations after initial salt formation; and

the potential for spatial separation of sequentially precipitated salts.

The precise mineralogy of carbonate and sulfate salts is highly sensitive to temperature conditions; chloride salts, however, show little temperature sensitivity. Many carbonate and sulfate salts also undergo temperature-dependent transformations after the initial salts precipitate. Salts precipitated in an underwater environment will experience a more narrow range of temperatures and a slower rate of temperature change than will salts precipitated at the ground surface.

The mineralogy of carbonate and bicarbonate salts is sensitive to the amount of dissolved carbon dioxide present in the water from which the salts precipitate. Many carbonate and bicarbonate salts also exhibit carbon dioxide-dependent mineral transformations. Dissolved carbon dioxide concentrations may be more variable and can reach higher concentrations in an underwater environment than water in the pore spaces of a surface soil or sediment.

Many carbonate and sulfate salts undergo hydration and dehydration reactions. Some hydration reactions involve amounts of water available only in an underwater environment. Hydration of burkeite, for example, can require 10-20 molecules of water for each molecule of salt.

Underwater precipitation of salt beds typically results in horizontal and vertical zonation of different salt minerals, as the different salts precipitate in sequence as they reach saturation concentrations in the lake water. The slow rate of temperature change in a large body of water enhances this effect. The physical dimensions of the capillary film of water producing surface evaporative salt deposits preclude such spatial zonation patterns in surface evaporite deposits. Spatial zonation of different minerals in a surface

evaporative salt deposit would indicate a moving zone of evaporation, probably accompanied by changes in salinities and dissolved mineral content of the evaporating water.

The pressure to which the salt minerals are exposed is a fifth potential factor differentiating underwater and surface salt formation. Pressure is probably relevant only for deep saline lakes or marine conditions. The literature reviewed by SWRCB consultants does not suggest that air and water pressure considerations are important for comparisons of Owens Lake and Mono Basin.

Salt Minerals Identified at Owens Lake

Smith and Friedman (1986), Saint-Amand et al. (1986), and Smith et al. (1987) have noted that many of the carbonate and sulfate salts present in the Owens Lake salt deposits undergo rapid transformations and phase changes in response to changes in temperature, humidity, and carbon dioxide concentrations. As a result, the mineral composition of salt samples (particularly those collected during cool periods) will change significantly before the samples can be analyzed in a laboratory. Laboratory analyses often detect only the products of mineral transformations and not the minerals that were present in the field. The researchers noted above have used a variety of techniques to estimate the mineralogy of salt deposits presently found at Owens Lake. Many of the salt minerals believed to be present at Owens Lake also can be expected to occur in the evaporative salt deposits found at Mono Lake.

The major salt minerals expected to be present in the surface layer of the Owens Lake salt deposit during different seasons can be categorized into four chemical groups as follows:

Sodium carbonates:
   -    natron (a decahydrate),
   -    thermonatrite (a monohydrate),
   -    sodium carbonate heptahydrate,
   -    sodium carbonate dihydrate, and
   -    anhydrous sodium carbonate (a noncrystalline salt).

Sodium carbonate-bicarbonate double salts:
   -    trona (a dihydrate).

Sodium sulfates:
   -    mirabilite (a decahydrate),
   -    thenardite (a crystalline anhydrous salt),
   -    sodium sulfate heptahydrate, and
   -    anhydrous sodium sulfate (a noncrystalline salt).

\# Halides:
- halite (rock salt).

All these salts are probably present in the salt deposits at Mono Lake during some seasons.

Several additional salt minerals are known to occur in the Owens Lake salt deposits but may occur only in the deeper consolidated layers of the deposits. It is uncertain whether the following salts occur in the surface layers of the Owens Lake salt deposits or in the Mono Lake salt deposits:

\# Sodium bicarbonates:
- nahcolite (a crystalline anhydrous salt).

\# Sodium carbonate-sodium sulfate double salts:
- burkeite (a crystalline anhydrous salt).

\# Sodium carbonate-calcium carbonate double salts:
- pirssonite (a dihydrate),
- gaylussite (a pentahydrate), and
- shortite (a crystalline anhydrous salt).

According to Saint-Amand et al. (1986), nahcolite formation may be prevented in a surface evaporative salt deposit by low carbon dioxide concentrations. Burkeite is a temperature-sensitive salt that forms only at temperatures above 57°F; trona and mirabilite or thenardite formation may be more likely in surface evaporative deposits.

As indicated above, most of the major salts expected in surface evaporative deposits are hydrated. Hydrated salts include water molecules chemically bound to the salt molecule. A monohydrate has one water molecule bound to each salt molecule, a dihydrate has two water molecules bound to each salt molecule, a pentahydrate has five water molecules bound to each salt molecule, a heptahydrate has seven water molecules bound to each salt molecule, and a decahydrate has ten water molecules bound to each salt molecule. Anhydrous salts do not contain any chemically bound water molecules.

The amount of water contained in hydrated salts can be substantial. Natron is almost 63% water by weight; mirabilite is almost 56% water by weight. The hydration and dehydration reactions of carbonate and sulfate salts are largely responsible for variations in the susceptibility of salt deposits to wind erosion.

Salt Deposit Formation Processes

The mineralogy of a salt deposit is determined by the interaction of several factors: salt formation temperature, effects of moisture addition, dehydration reactions, and phase changes induced by salt deposit

temperature changes. Although the salt deposits at Owens Lake and Mono Lake have formed in different ways, ongoing salt formation processes at the surface of the Owens Lake salt deposit provide insight into the evaporative salt deposits at Mono Lake. The following discussion is based largely on the process described by Saint-Amand et al. (1986) for Owens Lake but seems to be a reasonable estimate of the process occurring at Mono Lake.

Initial Salt Precipitation

The salts formed when saline water evaporates at the soil surface depend primarily on the temperature of the saline groundwater when saturation concentrations are reached for different salts. The saturation concentrations for sodium carbonate and sodium sulfate salts depend strongly on temperature; the saturation concentration for sodium chloride changes only slowly with temperature. Thus, sodium chloride can precipitate as halite at any temperature while the mineralogy of carbonate and sulfate salts varies at different temperatures.

At temperatures below 50°F, carbonate salts crystallize as natron and sulfate salts crystallize as mirabilite. At temperatures of 50-65°F, carbonates precipitate as trona and sulfates continue to precipitate as mirabilite. At temperatures above 65°F, carbonates continue to precipitate as trona and sulfates precipitate as thenardite. As noted above, halite can precipitate at any temperature if the salt solution reaches saturation conditions.

Natron and mirabilite are heavily hydrated salts that can precipitate at cool temperatures from relatively dilute salt solutions. Because these salts are heavily hydrated, their formation rapidly removes water from the solution, increasing its salinity and causing precipitation of more salts. The amount of water removed from the salt solution by formation of hydrated salts may exceed the amount of water lost through surface evaporation.

Moisture Addition Effects

If sufficient water becomes available from precipitation or surface flooding, the salt deposit will dissolve and a new cycle of salt deposition will begin. A slight rainfall will result in formation of hydrated salts at any season if the temperature falls below the dehydration temperature of the salts. Similarly, moisture available from dehydrating salts (see below) may dissolve some salts or allow others to become hydrated. Moisture and temperature effects can be linked as a result of evaporative cooling.

Dehydration Effects

As long as natron and mirabilite remain cool and damp, they remain stable. Once permitted to dry, natron and mirabilite quickly dehydrate to amorphous, noncrystalline powders. Natron dehydrates to

anhydrous sodium carbonate and mirabilite dehydrates to anhydrous sodium sulfate. The process can be hastened by osmotic transfer of water of hydration to halite.

During cool weather, crystals of mirabilite or natron can form on a wet substrate following a rain and then dehydrate in cool dry air to an amorphous powder. Mirabilite (a sulfate salt) is especially prone to this process, as mirabilite crystallization occurs at temperatures that are too warm to allow natrite (a carbonate salt) to form.

The dehydration of natron and mirabilite have important effects on the physical condition of the salt deposit. Dehydration converts crystalline salts to noncrystalline powders. Equally important are the significant volume changes that occur with dehydration (or rehydration) reactions.

Dehydration of natron to anhydrous sodium carbonate is accompanied by a volume reduction of 79%. Dehydration of mirabilite to anhydrous sodium sulfate is accompanied by a volume reduction of 76%. Rehydration of sodium carbonate to natron results in a volume increase of 375%. Rehydration of sodium sulfate to mirabilite results in a volume increase of 315%. These volume changes can disrupt the cohesion of a cemented salt crust even when natron and mirabilite are only modest components of the crust.

Temperature Change Effects

In addition to the dehydration reactions discussed above, carbonate and sulfate salts undergo other temperature-dependent transformations. The precise transformations depend on a combination of temperature, moisture availability, and carbon dioxide availability.

The simplest transformations seem to involve the sulfate salts. As temperatures increase, mirabilite dehydrates to anhydrous sodium sulfate if exposed to dry air. Any mirabilite present in deeper portions of a salt deposit releases its water of hydration and redissolves. The redissolved sulfate salt can precipitate later as either thenardite or mirabilite, depending on temperature. Although the literature reviewed is unclear, it seems to suggest that other polyhydrate sodium sulfate salts undergo comparable reactions.

As temperatures increase, natron dehydrates to anhydrous sodium carbonate if exposed to dry air. Natron present in deeper portions of a salt deposit will generally transform into trona. If salt deposit temperatures rise to extremely high levels, trona decomposes to thermonatrite. On cooling, thermonatrite can transform back into trona if some moisture is available. At cool temperatures and with adequate moisture available, trona can convert back into natron.

Factors Affecting the Erodibility of Salt Deposits

The erodibility of salt deposits is affected by conditions and factors common to other substrates: surface moisture conditions, wind speeds above the threshold wind velocity for various salt deposit conditions, the size of the exposed area, and the presence of saltating particles that can abrade any salt crust. A factor of special relevance to salt deposits is the physical structure of the deposit. Unlike most sediment types, the physical structure of a salt deposit can change on daily and seasonal cycles.

The physical structure of a salt deposit is determined largely by the mineralogy of the salts forming the deposit. As discussed above, the mineralogy of a salt deposit is determined by the interaction of several factors: salt formation temperature, effects of moisture addition, dehydration reactions, and mineral transformations induced by temperature changes.

Salt deposits dominated by halite have a hard, crystalline, cemented texture highly resistant to wind erosion. Dust storms are rare from salt crusts formed primarily from halite (Saint-Amand et al. 1986).

Salt deposits dominated by carbonate or sulfate salts can have a variety of textures, most of which are more subject to wind erosion than deposits dominated by halite. Deposits dominated by crystalline salts with low degrees of hydration (e.g., trona, thermonatite, and thenardite) present a hard, cemented crust that resists wind erosion. Deposits dominated by salts with a higher degree of hydration (e.g., trona and mirabilite) will have a weaker crust more susceptible to wind erosion. Deposits dominated by natron and mirabilite will be protected from significant wind erosion by their high moisture content rather than by a well-cemented crust but can easily transform into a powdery deposit of noncrystalline anhydrous salts. Deposits of anhydrous sodium carbonate and sodium sulfate have little resistance to wind erosion.

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